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RAPID CREATION OF MULTISPECTRAL TERRAINS FOR USE IN IN-BAND SCENE GENERATION AND OTHER ANALYTICAL TOOLS

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ABSTRACT

Synthetic terrain generation and scene generation is a critical component of performing meaningful simulation assessments across many simulation domains. The U.S. Army Combat Capabilities Development Command Aviation and Missile Center (CCDC AvMC) has developed a process for rapidly generating and characterizing large-scale, multispectral terrain models and thermal signatures for use in a wide range of simulation tools from ground vehicles and air platforms to smart weapons and AI algorithms. This process has allowed the replacement of legacy terrain generation methods of on-site collections or statistics-based models with high-fidelity, physics-based terrain signature modeling at a fraction of the schedule and cost by leveraging modern high-performance computing paradigms and algorithms. This allows for rapid generation of terrain models of any location in the world at any time of day or season.

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1. INTRODUCTION

Many current technologies, from ground vehicles and air platforms to smart weapons and AI algorithms, rely on digital simulations to predict and assess performance, drastically reducing development cycle timelines. For many of these technologies, a major limiting factor in simulated performance analysis is both the availability of high-fidelity multispectral terrain models encompassing a wide range of relevant scenarios and a way to render the terrain models as physically accurate scenes for use in these simulations. This lack of available data results in simulated analysis on a much smaller range of scenarios than desired, limiting the effectiveness and/or statistical certainty of the study.

Historically, terrain models have either been derived from empirical collections from on-site collection campaigns or from statistical models. On-site collections are limited by expense in both labor and schedule. Additionally, data collections are limited to terrains to which the modeler has physical access, making OCONUS areas with denied access impossible, and are limited to the weather conditions present at the time of the collection. These factors greatly limit the total number and variability of available terrain models for use in simulation. In contrast, statistical models allow for a wide range of variability, but are based on models that may not accurately capture the real-world phenomenology and can generate terrain models that are not representative of real-world signatures.

In order to address these limits, CCDC AvMC has developed a process and toolset shown in **Figure 1** to rapidly generate high-fidelity, physics-based, multispectral terrain models. These terrain models typically span hundreds of square kilometers at resolutions of 0.5 to 0.25 meters and consist of all necessary data needed for use in various simulations and scene generators including topography, classification maps, material properties, thermal signatures, and discrete elements in the terrain such as vegetation, buildings, bridges, and other natural and manmade structures. This process allows the generation of terrain models anywhere in the world using high-resolution multispectral satellite imagery to allow the creation of terrain models for approximately 10% or less of the cost of a traditional on-site collection effort. CCDC AvMC has also developed the Common Scene Generator (CSG), which produces physically accurate renderings of fully-synthetic imagery for use in simulation analysis and performance assessment.

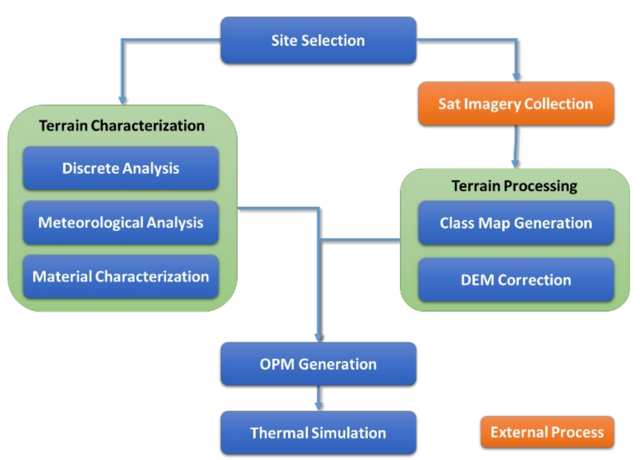

Figure 1: Synthetic Terrain Generation Process

2. SITE SELECTION AND IMAGERY COLLECTION

The process begins with the selection of a region of interest (ROI) for the terrain to be modeled. This selection process can be based on various sets of criteria dependent on the needs and requirements of the simulation. For some programs, the required area is a specific known region and, in that case, a simple labeling of the ROI boundaries is sufficient to begin the satellite imagery collection process. However, in other cases, a specific location is not necessary, but instead a specific set of characteristics is required. For example, a program may require a terrain in a general region of the world with defined soil types, vegetation density and type, and climate characteristics. In these instances, a terrain analysis is performed and several potential ROI's are selected. These ROIs are then presented to the program as well as to the satellite imagery providers to determine which areas best meet the program needs while also minimizing potential collection issues that may arise such as snow-cover or high chances of cloud cover that can obscure the image and prevent accurate material classification.

Once the ROI has been selected, the area is provided to the satellite provider for collection. The imagery provided by the collection effort typically contains several data products seen in **Figure 2**, including 8-band multispectral imagery at resolutions of 1.2 meters, pan-sharpened color imagery at resolutions of 0.3 meters, and a gridded Digital Terrain Model (DTM) and Digital Surface

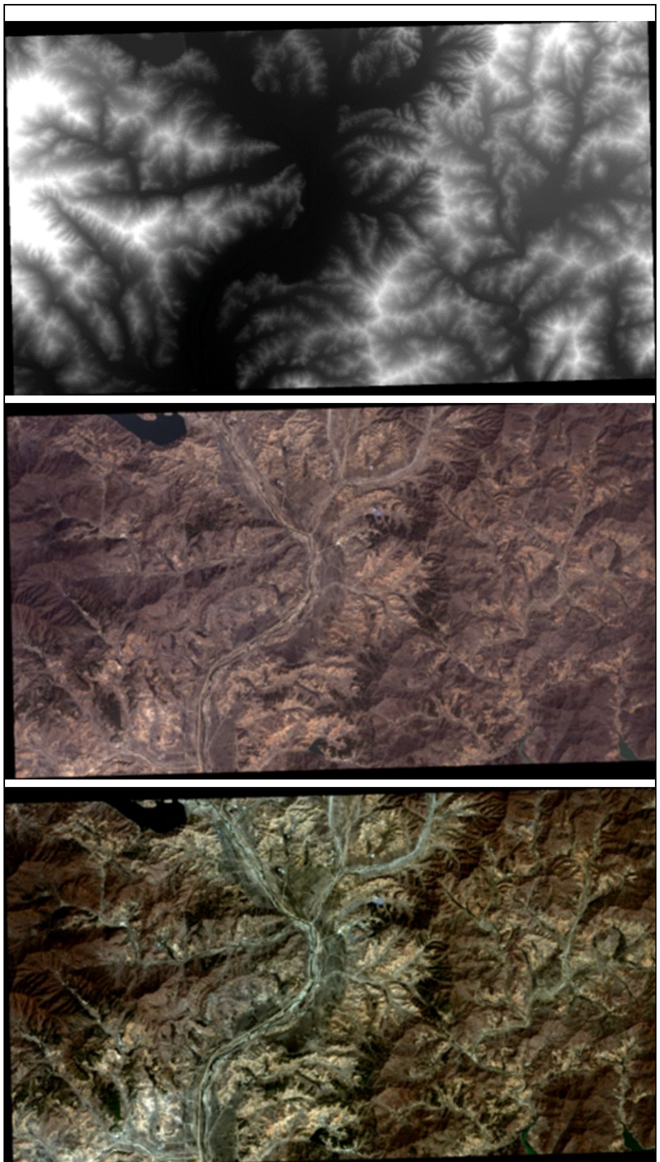

Figure 2: DTM (top), 8-band multispectral imagery (middle) and 3-band pan-sharpened imagery for the same area.

Model (DSM) at resolutions of 0.5meters. A DTM contains the topographical elevation data of a terrain at ground level as if all vegetation and buildings were removed from the scene while a DSM contains topographical data of the terrain with all vegetation and buildings represented in the data.

3. TERRAIN CHARACTERIZATION

Once the site selection has occurred, the terrain characterization will begin, allowing for the generation of all data necessary to generate an accurate terrain model suitable for use in scene generation applications. This characterization process consists of several steps, many of which can be completed in parallel to the satellite collection effort, and are described in the sections below.

3.1. Discrete Analysis

Determining the types and locations in the scene of faceted, discrete object models is one of the first steps in characterizing the terrain. These objects are typically large vegetation such as bushes and trees and manmade structures such as buildings and bridges.

This process generates data that will drive additional steps later in the overall process such as the material analysis and object placement steps. Online databases and published literature investigated to determine the flora and building types present in the scene. From this data, a library of available models is selected to populate the scene. In some cases, the types of discrete objects necessary to be placed in the scene are not available in the existing library. In these instances, tools have been developed to automatically build the required models. For vegetation, a tool has been

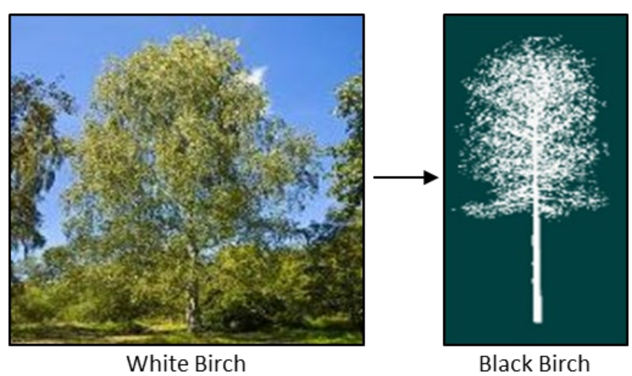

Figure 3: Surrogate model (Black Birch) used for actual model (White Birch) in Europe Scene

developed as part of the Rapid Terrain SBIR to automatically generate faceted models is used to define characteristics such as leaf size, branching height and angle, and total height. Additionally, the process identifies manmade structures that are characterized with appropriate building materials via inspection of local building codes. In some cases, a direct match for a particular building or vegetation model may not be available for a particular discrete object. In these cases, either a surrogate model is used, as shown in **Figure 3**, or a new model will be generated.

3.2. Meteorological Analysis

In order to create a physically accurate signature model that represents a specific time and day, meteorological data reflecting that particular time must be collected. In the simplest case, the modeled day and time is a historical time and the meteorological data can simply be collected from a measurement at that time and place. In the case of recreating test events, meteorological conditions can be directly imported into the scene from data collected as part of the test. For modeling non-test scenarios, weather data can be collected from a nearby weather station, many of which are publicly available online. Modeling of future scenarios obviously prevents direct measurement of conditions. For these cases, appropriate climatological data is used.

In many cases, the available data may not contain all parameters that are required for modeling. To generate the required data, empirical models are typically used to derive the necessary data parameters for available data. As an example, for the thermal solver to generate accurate results, sky temperature and total solar irradiance values are necessary but are not collected as part of most weather station datasets. These values are instead modeled using the Meyers/Dale model for solar irradiance and the Swinbank/Cole model for the sky temperature [1] [2] [3].

3.3. Material Characterization

A major component, the accurate modeling of a multispectral scene for use in scene generation, is the material characterization effort. Material parameters are the primary driver of the generated signature, regardless of the band in which the scene is rendered. Although the most accurate way to perform a material characterization is to do an on-site data collection effort. This method still introduces issues in that only a small number of samples are usually able to be collected and the collection only represents a single time of day and year. In addition, in many cases, an on-site collection effort is not feasible, due to either cost and scheduling or simply lack of access to the modeled terrain. To solve this issue, a process was developed to generate accurate material properties from publicly available databases and documentation.

One such source is the United States Department of Agriculture's (USDA) Web Soil Survey [4]. This online database contains physical and engineering properties for soils across the entirety of the United States and can be used to generate material characteristics for many necessary parameters used in the terrain generation process. An additional benefit of this database is that it contains a range of values for each parameter, which is more representative of the real world. By incorporating this variability, the natural intra-class variation seen in the real world can be introduced into the synthetic simulations, producing a highly accurate signature model.

The Web Soil Survey, while a robust data resource, does not provide all the necessary parameters required for thermal simulation and scene generation, such as absorptivity, emissivity, and reflectivity, which are required for accurate EOIR and RF signature models. To generate these parameters, either direct measurements from publicly available resources or empirical models that can derive needed parameters from available data are used. One example is the thermal conductivity value necessary for accurate thermal simulation, which is derived from data available in the Web Soil Survey using the Johansen Method [5]. Additional resources used to define the required material characterization parameters include the CRC Handbook of Tables for Applied Engineering Science as well as other published scientific documents [6] [7] [8].

3.4. Class Map Generation

The class map generation process converts the color imagery provided by the satellite collection into gridded class maps used by the thermal solver and scene generators. The satellite color imagery has been typically provided as an 8-band multispectral image at 2.0m resolution as well as a 3-band pan-sharpened image at 0.5m resolution, but recent improvements to imaging satellite capabilities have allowed for resolutions up to 1.2m multispectral and 0.3m pan-sharpened imagery.

Once the color imagery has been received, it is imported into commercial GIS software such as qGIS or ArcGIS. From there, it is processed using a combination of supervised and unsupervised classification processes into a map where each material is classified and binned into an array of classes such as soil, grass, or asphalt as seen in **Figure 4**. A typical terrain model can have anywhere from 15 classes for a simple desert terrain to 40+ classes for a complex terrain with variation in vegetation, soil types, and manmade surfaces.

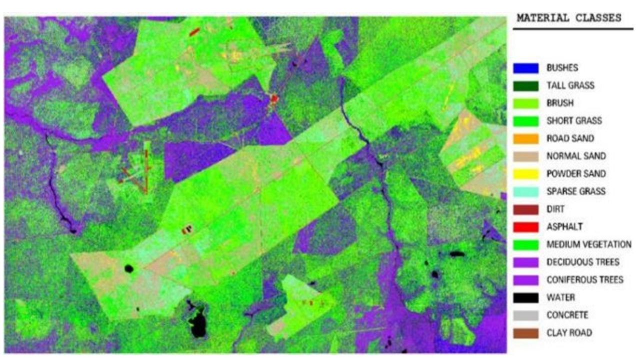

Figure 4: Classification Map

In addition to a Class Map, the process also generates an Extended Class Map. The Class map contains the materials present on the ground of the terrain, similar to the DTM that describes the terrain height. The Extended Class Map describes the materials present at the surface of the terrain from a birds-eye point of view similar to the DSM elevation model. For example, when a forest is present in a scene, the Class Map may indicate that soil is present at that location where the Extended Class Map would indicate that a tree material such as leaves is present at that location. The combination of these two maps can be used in the scene generator for a multitude of purposes such as returning reflected energy obscured by vegetation in RF channels and enabling memory optimizations by removing the number of discrete models needed to be rendered.

3.5. Object Placement Mapping

The final step in the characterization of a terrain is the object placement mapping which will define the location of each discrete object in the scene. This process consists of both a geo-typical and geo-specific mapping. Geo-typical mapping consists of placing objects in the scene in a way that is typical of what would be found in the scene in the real world. This process is used for the majority of the vegetation objects in the scene. For instance, for a forest present in the real-world terrain at a given location, a geo-typical mapping would also have a forest in that location. However, each individual tree placed in the scene would not correspond with a tree location in the real world. As most simulations are not concerned with exact placement of every tree in a forest, this is acceptable for most synthetic scenes. For the instances where a specific discrete does need to be in a specific location, a geo-specific mapping is performed so that a discrete object is placed at the exact location where it appears in the real world. This can be seen in **Figure 5** where the trees are placed using a geo-typical placement and the buildings are mapped using a geo-specific placement.

The geo-typical mapping process is carried out by an automated discrete placement tool. This tool takes input from the user in the form of a DEM, Class Map, and parameters defined by the user to control the procedural placement of the objects using a Poisson-disk sampling method [9]. The user defines parameters on a per-class basis to include discrete types, spacing, size and scale, and chance of occurrence. This tool allows the rapid and automated placement of millions of discrete objects in locations that would be consistent with what is encountered in the real world for a given terrain model.

Figure 5: Geo-Typical (trees) and Geo-Specific (buildings) Placement of Objects in a Scene

4. THERMAL SIMULATION USING HOTTS

For simulations based in the thermal IR bands, an accurate thermal signature is required for analysis and assessment. In order to generate physically accurate thermal signatures of large-scale terrain models, CCDC AvMC has developed the Highly Optimized Terrain Thermal Solver (HOTTS) tool. HOTTS is designed to use modern massively-parallel computation resources to generate large-scale terrain signatures suitable for use in high-fidelity scene generation toolsets. The HOTTS tool is capable of generating diurnal signature models for areas greater than 100 km2 containing millions of discrete objects in 4-6 hours on a single desktop workstation. The HOTTS tool allows a simulation analyst to generate a large number of high-fidelity synthetic signatures representing various seasons of the year and times of day.

4.1. Capabilities

The rapid runtime of the HOTTS tool has allowed for the development and inclusion of many capabilities not available in other high-fidelity thermal solvers. These capabilities include dynamic wind modeling, radiation exchange interactions, multiple types of shadowing effects, dynamic water content and soil properties due to precipitation, intraclass variation, and very-high-fidelity feature insertion.

Many capabilities of the HOTTS tool have been developed in order to address the issue of intraclass variation. Most thermal solvers assign a single environmental state and material value to all instances of a material in the terrain. The result of this can lead to a cartoonish “paint-by-numbers” thermal signature where all instances of a material have the exact same temperature value.

In contrast, HOTTS allows a range of material properties to be used based on the material characterization effort discussed in section 3.3 and uses spatially correlated noise parameters derived from collected imagery to create variation in the material properties on a per-post basis. In addition, HOTTS has the capability to adjust material properties in real-time based on the local weather conditions, adjusting the material properties based on how much water is present in the soil. This results in a natural signature than would be generated by a single material definition for an entire class type as can be seen in **Figure 6**. This figure shows a road, indicated by the yellow band, in a terrain model. The graph in each image shows a plot of the temperature value along the thin line running the length of the road. Without this variation, the thermal signature results in a uniform temperature across the length of the road as shown in the bottom image. By adding the material variation, the plot indicates a noisier, but spatially correlated, temperature profile that is consistent with real-world phenomena.

HOTTS also has the ability to generate high-fidelity shadows for all objects in the scene. Many of the synthetic scenes generated contain between 50 and 100 billion facets. Using traditional ray-tracing algorithms to calculate the shadowing in a scene could take hours per time step. To address this issue, a shadowing algorithm was developed in which each type of shadowing is handled separately, including terrain-on-terrain, discrete-on-discrete, discrete-on-terrain, and terrain-on-discrete. By leveraging image-processing techniques and using a combination of high-fidelity techniques in areas of high importance and runtime-efficient techniques in areas of low importance, HOTTS can generate shadow maps for an entire terrain in less than a minute, increasing the overall fidelity of the synthetic signature modeling process. An example of the shadowing on a bridge model can be seen in **Figure 7**.

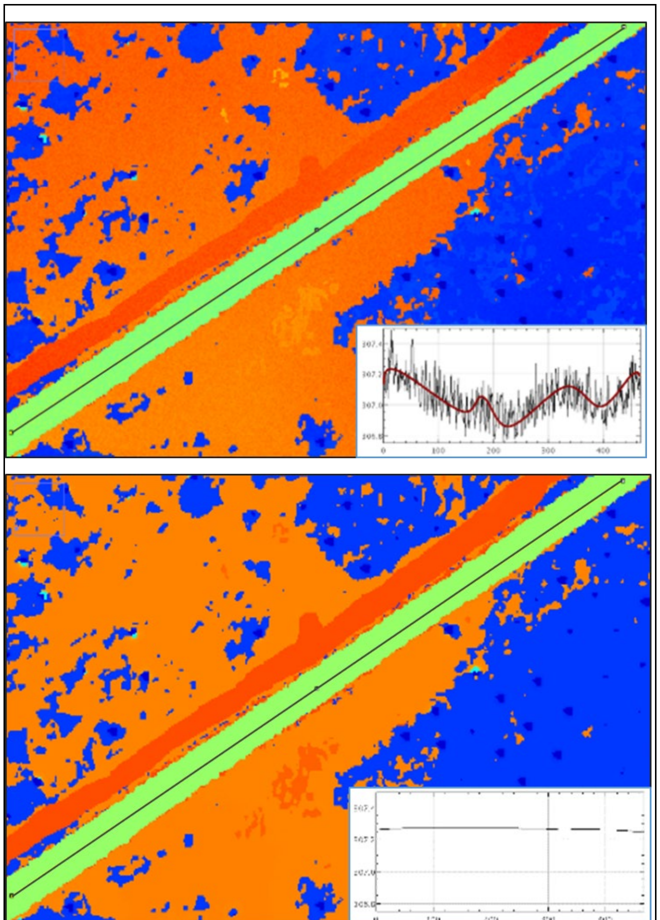

Figure 6: Temperature of a Road Without (top) and With (bottom) Dynamic Material Variation

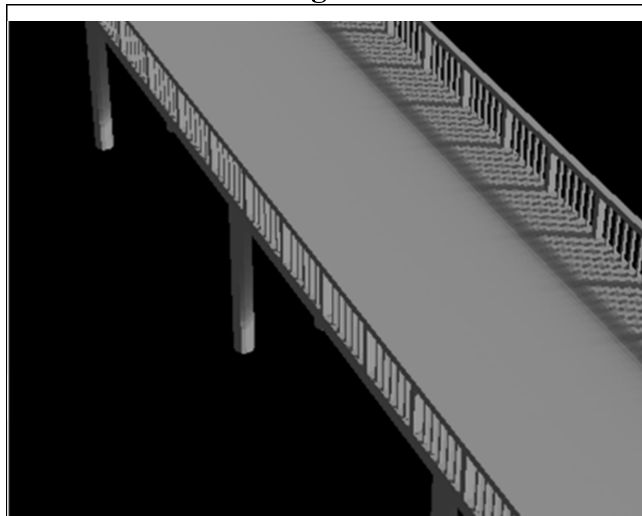

Figure 7: Thermal Shadowing on a Bridge

When the fidelity required by a simulation is greater than is possible to be generated by the half-meter resolution typically created by the terrain generation process, HOTTS also offers the capability to insert very-high resolution faceted models into the scene. This capability allows the insertion and thermal solution of small scene insets as well as insertion of thermal signature models generated by an external thermal solver such as the VESPA thermal solver used by the U.S. Army Engineer Research and Development Center (ERDC). These models can be built at very high resolutions from a multitude of sources, including aerial LiDAR data, and are capable of exceeding sub-centimeter resolutions. This allows for multi-resolution modeling, placing higher-resolution data at areas of importance to the simulation as can be seen in **Figure 8**. The high-resolution inset in the middle of the image is at 1 cm resolution and shows detail not present in the surrounding 0.5 m terrain.

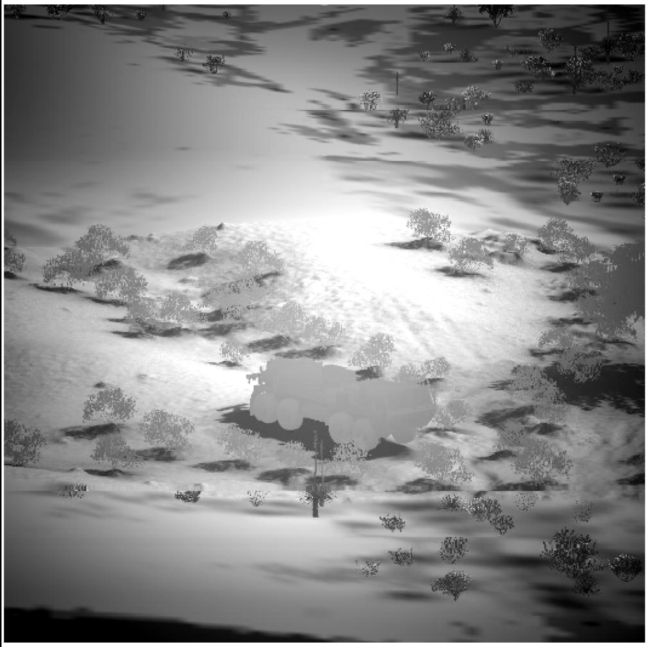

Figure 8: Insertion of High-Res Scene

4.2. Validation

An important aspect of any thermal solver tool is the confidence that a modeler has that the end product will be representative of the real world. A thermal solver that cannot accurately replicate a real-world scene cannot be trusted to generate realistic results for predictive scenarios. To this end, the HOTTS toolset has undergone a limited validation effort to assess its accuracy. Since validation is only as accurate as its inputs, validation was not performed via a scene-to-scene comparison. The introduction of the complex characterization data associated with the scene would make direct comparisons difficult. Instead, HOTTS simulations of a single material, flat plane were compared to collected thermocouple data. The materials used are a dirt road and a sand road collected at Eglin AFB on October 16, 2011.

The table and charts below show the results generated from the HOTTS thermal solver compared to the measured data samples. As seen in **Table 1**, the average difference is less than a degree K for both materials, with a maximum delta of 1.5K for the sand road and 0.6K for the dirt road. The charts in **Figure 9** indicate that HOTTS predicted solution is within reasonable expectations for accuracy and behave as expected, and therefore is able to generate credible signatures for use in synthetic scene generation.

	Dirt Road	Sand Road
Max Delta (K)	0.610	1.591
Average Delta (K)	0.255	0.566

Table 1: Delta between HOTTS predicted temperature and collected thermocouple data

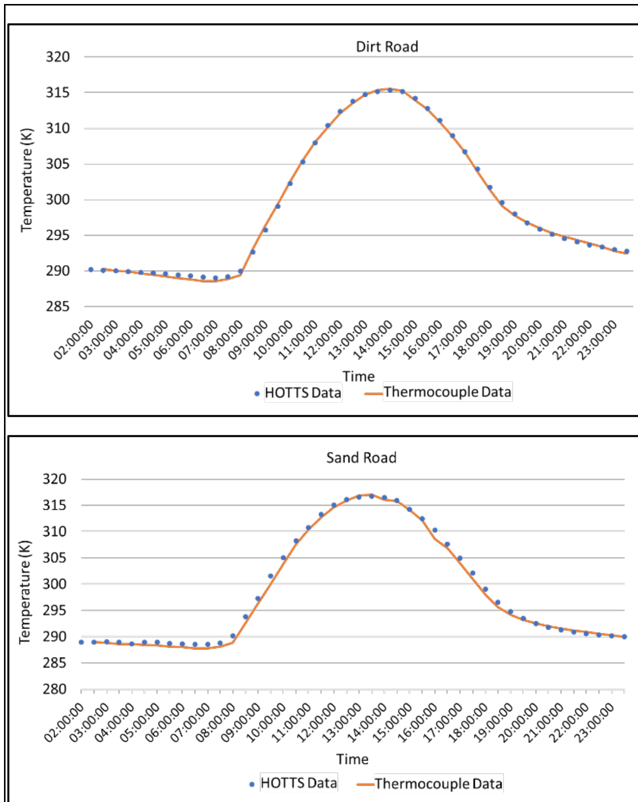

Figure 9: HOTTS results comparison to measured data for a dirt road (top) and sand road (bottom)

5. SCENE GENERATION

In order to assess the performance of a system simulation with a high degree of accuracy, the simulation must be tested against conditions that it would encounter in the real world. A scene generator allows a system to be assessed using high-fidelity imagery that accurately models the physical energy that would impinge upon a given sensor. By incorporating synthetic terrain models, a scene generator provides realistic clutter environments to be projected to the sensor model, allowing tactical algorithms in a simulated environment to react as they would in real-world scenarios. CCDC AvMC has developed CSG as a high-fidelity scene generator capable of generating physically accurate imagery in a number of bands, including Long-wave Infrared (LWIR), Mid-wave Infrared (MWIR), Radio Frequency (RF) such as Millimeter Wave (MMW), and Semi-Active Laser (SAL).

By integrating a scene generator into a simulation, an engineer is capable of analyzing exactly how a system would respond to a given scenario at a fidelity that is typically not available using a statistical model to drive the sensor. Statistical models are limited by the amount of data available the generate the models and are not able to model phenomena that was not present in the dataset from which the statistical model is derived such as countermeasures and atmospheric affects such as dust and smoke. CSG gives the simulation analyst a number of tools and capabilities to test a simulation's performance. These capabilities include multiple sensors and bands, multiple target models, dynamic target and sensor motion, countermeasures, atmospheric effects, and realistic terrain and clutter modeling. An example of the imagery generated by CSG can be seen in **Figure 10**, which shows an LWIR scene with convoy of a tank and two trucks driving along a treeline. Additional capabilities shown in Figure 10 include physically correct thermal signatures for the terrain, vegetation and dynamic dust models controlled by wind, vehicle speed, vehicle type, and surface material types. By integrating a scene generator such as CSG into a sensor simulation and leveraging the terrain modeling process described in this paper, highly accurate simulation assessments can be made as opposed to using statistical modeling alone.

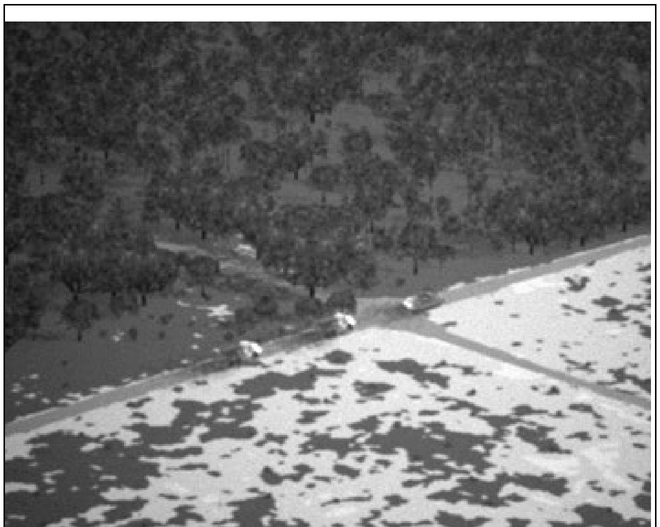

Figure 10: Synthetic LWIR Image of a Convoy along a Treeline Rendered using CSG

6. USE CASES

The rapid generation of high-fidelity synthetic scenes allows several new capabilities and enhancements across a broad range of use cases from simulation performance assessments to generation of image libraries for use in machine learning training and analysis. Several of these use cases are described in the sections below.

6.1. Simulation Performance Assessment

One of the primary uses for the multispectral terrain generation process has been for sensor-based simulation performance assessments. These performance assessments are designed to test the performance of a given system across a wide range of conditions that would be expected to be encountered in real-world scenarios. The terrain generation process has been used to develop both CONUS and OCONUS terrains that are used in multiple Army and Air Force programs. This process has allowed these programs to increase the number and breadth of scenarios available in a performance assessment. Increasing the variation available in the assessment gives highly accurate prediction of how the system would behave in real-world scenarios.

6.2. Test Planning and Analysis

Pre-test planning and post-test reconstruction is another common use of the terrain generation process. When planning a live test event, it is important to have accurate predictions of how the system will behave in the test. Often, a pre-test simulation will reveal a flaw in the test setup that could lead to a test event failing to collect the intended data. By creating accurate models of the test area and conditions, pre-test simulation analysis predicts how the simulation will behave in a live test event with a high degree of accuracy and increases the likelihood of a successful test.

Post-test reconstruction consists of recreating a terrain model using the conditions collected during a test event. Accurate post-test reconstruction efforts allow simulation developers to compare actual test data to simulation data, validating that the simulation reflects the performance of the real-world system. In addition, post-test reconstruction using synthetic scenes can allow for analysis of test failures due to unexpected variances in the real-world test conditions.

6.3. Machine Learning

Many programs are beginning to transition to machine learning algorithms to drive seeker algorithms and system behavior. However, a common limitation of many of these programs is the lack of robust training and evaluation data sets. Training data is typically limited to empirical data collected during test events and this lack of variation can lead to biases in the resultant machine-learning algorithms. The process of generating high-fidelity synthetic imagery can solve this issue by facilitating the generation of large image sets spanning large varieties of clutter, locations, targets, seasons, and weather.

7. CONCLUSION

The multispectral terrain process has enabled the rapid generation of multiple terrain models that have been employed across a number of DoD programs to increase the accuracy and fidelity of a wide range of sensor simulations. The process has been shown to replicate terrain models and multispectral signatures with a high degree of accuracy across a wide range of real-world locations. This process can be leveraged by numerous technologies that could be enhanced by having access to a large database of highly variable synthetic scenes.

Many of the processes and algorithms outlined in this paper have been documented in white papers during the development of the terrain generation process. These papers can be made available on request by the Department of Defense and U.S. DoD contractors.

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